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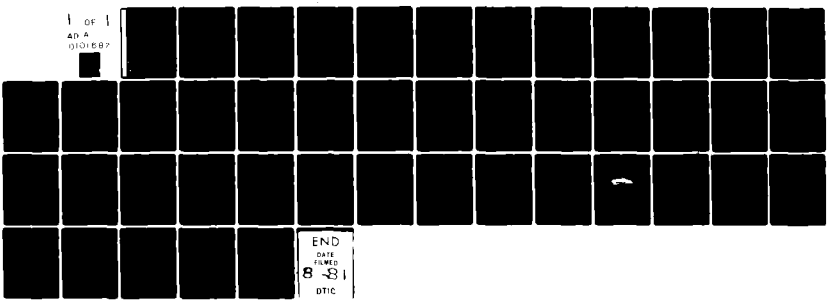

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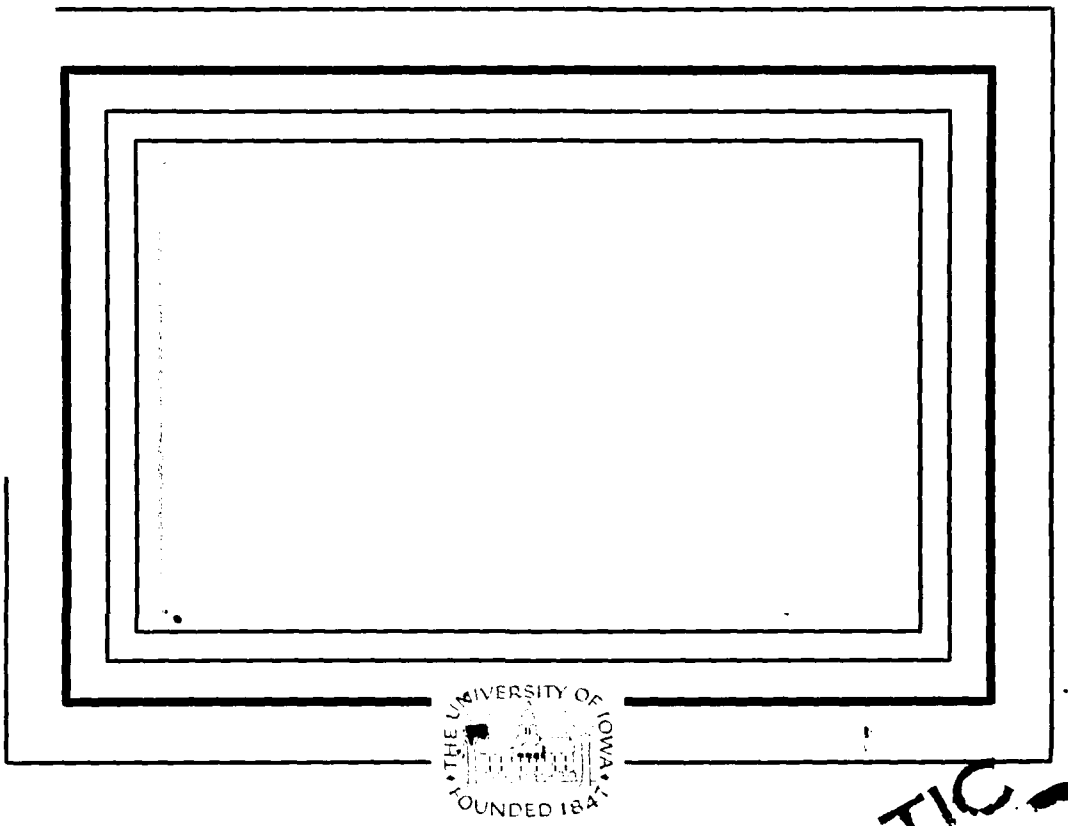

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER U. of Iowa 81-20	2. GOVT ACCESSION NO. AD-A101687	3. RECIPIENT'S CATALOG NUMBER --
4. TITLE (and Subtitle) AURORAL KILOMETRIC RADIATION: A THEORETICAL REVIEW		5. TYPE OF REPORT & PERIOD COVERED Progress, May, 1981
		6. PERFORMING ORG. REPORT NUMBER --
7. AUTHOR(s) Crockett L. Grabbe		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C016
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Physics and Astronomy The University of Iowa Iowa City, Iowa 52242		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS --
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Electronics Program Office Arlington, Virginia 22217		12. REPORT DATE May 15, 1981 13. NUMBER OF PAGES 42
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

An earlier version of this paper was written while on a Science Applications' contract with the Naval Research Labs, which was funded by the Office of Naval Research. The present (completely revised) version was supported by NASA, while at The University of Iowa.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Auroral kilometric radiation
Nonlinear wave interactions
Loss cone instability
Beam instability
Wave-particle interactions
Soliton radiation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

[See reverse side.]

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Abstract

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U. of Iowa 81-20

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AURORAL KILOMETRIC RADIATION: A THEORETICAL REVIEW

by

Crockett L. Grabbe

DTIC
JUL 21 1981

May, 1981

To be published in Rev. Geophys. and Space Sci., Nov. 1981.

This research was supported by the National Aeronautics and Space Administration under Grant NGL-16-001-043 with NASA Headquarters.

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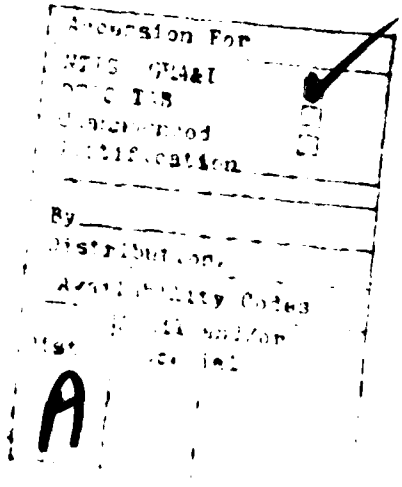
Abstract

A number of theories have been proposed in recent years to explain auroral kilometric radiation. These include an anisotropic velocity distribution instability, mode conversion of electron cyclotron waves to ordinary mode radiation, soliton radiation, beam driven instability of electromagnetic waves via low frequency turbulence, a loss cone instability, beating of coherent electrostatic waves, and beam amplification of electromagnetic waves via coherent density fluctuations. These will all be reviewed and comparisons of prediction made with observations. Emphasis will be placed on the three recent proposals.



I. INTRODUCTION

Auroral kilometric radiation (AKR) is a high-density radio wave radiation in the frequency band between 50 and 750 kHz, with a peak around 250 kHz, that has been observed emanating from the auroral zone. The radiation is too low frequency to penetrate through the ionosphere to Earth, so all observations have been made by satellite. The first observational study of AKR was made by Gurnett [1974], although it had previously been discovered by Dunckel et al. [1970]. Measurements have been made in the predominate source region at R ~ 2-3 R_E by Hawkeye I [Gurnett and Green, 1978], in the lower source region near 1.5 R_E by Isis I [Benson and Calvert, 1979], and outside the source as far away as R ~ 100 R_E by Voyager I [Kaiser et al. 1978]

The AKR is closely correlated with the occurrence of discrete auroral arcs, which are believed to be generated by intense inverted V electron precipitation bands [Gurnett, 1974]. More recent data indicate a direct correlation of AKR with the inverted V events [Benson and Calvert, 1979; Green et al., 1979]. The inverted V bands appear to contain high energy beams closely aligned along the magnetic field lines, with beam energies E_b ~ 5-15 keV or beam velocities v_b ~ 0.1 - 0.2 c [Matthews et al., 1976; Kaufmann and Ludlow, 1980; Sharp et al., 1980]. (An example of a high energy beam in the lower auroral with beam density to plasma density ~ 10^{-2} - 10^{-3} is shown in Figure 1.) The electron precipitation bands are the apparent energy source of AKR. When these bands are not present, no AKR is observed and only a diffuse aurora appears. The total estimated power output of AKR at peak is ~ 10^9 W, to be compared with the maximum power dissipated by the auroral particle precipitation of ~ 10^{11} W. This indicates a 1% conversion efficiency [Gurnett, 1974].

The AKR events are sporadic and bursty in nature. AKR data obtained in the source from Hawkeye I [Gurnett and Green, 1978] and Isis I [Benson and Calvert, 1979] show that the radiation is generated in the X-mode just above the local right-hand cutoff frequency. The polarization is further confirmed by direct measurements of the AKR polarization from Voyager I at R ~ 100 R_E using transverse monopole antennas [Kaiser and Alexander, 1978]. The Isis I measurements also show the radiation is generated within density-depleted regions in the auroral zone where $\omega_{pe} < 0.2\ \omega_{ce}$ (ω_{pe} is the plasma frequency and ω_{ce} the electron cyclotron frequency), and is primarily downcoming, making angles between 60° and 90° with respect to the local magnetic field [Benson and Calvert, 1979; James, 1980].

In this article, we will review several theories that have been proposed to explain the observed AKR, with emphasis on the three most recent theories, which appear to have greater promise. (For an earlier review, see Maggs [1978]). We will limit ourselves to terrestrial AKR, although some theories may be relevant to Jovian decametric radiation. (See Smith, 1976, for a recent review of Jovian decametric radiation theories.) Attention will be paid to the underlying physical mechanism of each theory, the specific predictions made by the theories, and how well they agree with observation. Suggestion for further observations which will test predictions for which evidence is presently unavailable will be made. It should be noted that the more recent theories have the advantage in that they were formulated with a greater abundance of data available. Thus, the extent to which a theory agrees with observation is not necessarily an indication of the ingenuity of the theory.

II. CONVERSION OF ELECTRON CYCLOTRON WAVE TO O-MODE

A mechanism of double mode conversion of beam radiation was proposed by Oya [1974] for Jovian decametric radiation, and was extended to AKR by Benson [1975]. There are three processes involved in this mechanism (see Figure 2). In the first process field aligned precipitating beams and/or thermal anisotropies create electron cyclotron wave turbulence. These waves propagate toward decreasing plasma density (in the -x direction) until they encounter the upper hybrid resonance: $\omega \cong \omega_{uh}(x)$. In the second process, the electron cyclotron waves convert to the slow X-mode (z wave, see Figure 3) at the upper hybrid resonance layer, reflecting back toward increasing density. The z waves then propagate into the plasma frequency cutoff layer $\omega \cong \omega_{pe}(x)$, where they convert into the O-mode (see Figure 4) in the third process. These waves propagate in the direction perpendicular to the density gradient and magnetic field and out to free space.

The predicted direction of the O-mode propagation is almost perpendicular to the background magnetic field, in agreement with observation. The efficiency of this conversion was found to be ~10%. Thus, the overall efficiency, which is the product of efficiencies of all three processes, is very unlikely to ever be the 1% that is measured for conversion of electron precipitation energy to AKR. Furthermore, the predicted polarization (O-mode) is in disagreement with recent observations. Thus we need a more direct mechanism.

III. COHERENT AMPLIFICATION OF GYROEMISSION BY VELOCITY SPACE INSTABILITIES

Melrose [1973] first set forth a general theory of coherent gyromagnetic radiation for application to several astrophysical phenomena, including the Jovian decametric radiation. He applied the theory specifically to a bi-Maxwellian distribution of streaming electrons with different thermal velocities perpendicular and parallel to the magnetic field, although the general approach could be applied to a number of different distribution functions. He showed that an electromagnetic instability arises from the velocity space anisotropy similar to the Harris instability [Harris, 1959], provided $\beta_\perp^2 > \beta_\parallel$ where $\beta_{\perp,\parallel} = [\kappa T_{\perp,\parallel}/m_e]^{1/2}/c$, and where $T_\perp$ and $T_\parallel$ are the electron stream temperatures perpendicular and parallel to the magnetic field.

In a later paper, Melrose [1976] applied this instability particularly to the problem of auroral kilometric radiation and Jovian decametric radiation. In this model, precipitating electron streams radiate at a low level in the RX mode at the Dopper-shifted beam cyclotron frequencies $\omega \cong n\omega_{ce} + k_\parallel v_b$, and this radiation is amplified by the instability. The dominant radiation was found to occur near $\omega \cong \omega_{ce} + k_\parallel v_b$ if $\omega_{pe} << \omega_{ce}$, and $\omega \cong 2\omega_{ce} + k_\parallel v_b$ if $\omega_{pe} > \omega_{ce}$. The first case corresponds to the plasma conditions observed from Isis I. The radiation at that frequency is accessible to free-space provided $k_\parallel v_b < \omega_{pe}^2/\omega_{ce}$. If the latter condition is satisfied, then the resulting frequency is just above the right-hand cutoff, in agreement with observation.

The condition for amplification of the RX mode by this mechanism typically requires $T_\perp/T_\parallel > 30$. The measurements of particle distributions in the lower aurora by Kaufmann and Ludlow [1980] do not show any significant thermal anisotropy, and there is no evidence of the existence of such large anisotropies, or mechanisms to produce them, elsewhere in the aurora. Thus, it is unlikely AKR could be produced by this mechanism. However, there are other instabilities which are capable of amplifying the Doppler-shifted beam cyclotron frequency, as implied by Melrose's general formulation. One such instability is the loss cone instability, which was proposed by Wu and Lee [1979] and is presented in Section VI. Another instability arises from nonlinear coupling to the beam through interaction with low frequency waves [Grabbe et al., 1980] and is presented in Section VIII.

IV. BEAM DRIVEN ELECTROMAGNETIC INSTABILITY VIA LOW FREQUENCY TURBULENCE

In the model proposed by Palmadesso et al., [1976], RX and LO modes propagating obliquely to the magnetic field are assumed to be present at noise levels, and to have their electric fields modulated by low frequency turbulence present in the aurora, which they speculated was driven by electrostatic electron cyclotron waves. Then beat wave could interact with the electron beam provided

$$\frac{\omega_o - \omega_i}{k_o - k_i} \approx -\frac{\omega_o}{k_i} \approx v_b \quad \begin{pmatrix} \omega_i << \omega_o \\ k_o << k_i \end{pmatrix} \tag{1}$$

where (ω_o, k_o) and (ω_i, k_i) are the frequency and wavenumbers of the electromagnetic wave and low frequency waves, respectively, and v_b the beam velocity. Thus the beam feeds energy into the electromagnetic wave and causes it to grow.

Palmadesso et al. found that in order to get sufficiently efficient transfer of beam energy to the electromagnetic wave, the beat wave of slow phase velocity $\omega_o/k_i << \omega_o/k_o \sim c$ was required to be almost a normal (electrostatic) mode of the system. For high frequency waves, this limits the frequency to $\omega_{ce} < \omega < \omega_{uh}$ (see Figure 5), which is the only regime with an appropriate normal electrostatic mode to couple to. As the two modes (both of which are amplified in this theory) propagate out to free space, only the LO mode is accesible (i.e., encounters no cutoff enroute) to free space because the RX mode is evanescent between ω_{uh} and ω_R, hence would be the polarization observed. This conclusion is in disagreement with the more recent polarization measurements.

The most efficient wave growth occurs for $\omega_{pe} < \omega_{ce}$, which is the case observed. Growth lengths of 50 km to a few hundred km are predicted, which are marginally adequate to produce the observed AKR levels. Recent observations have shown the low frequency turbulence (which was assumed incoherent) in the aurora appear to be strong coherent electrostatic ion cyclotron (EIC) waves [Temerin et al., 1979; Lysak et al., 1980]. This suggests modified versions of this theory may hold promise. Such a modified version is discussed in Section VIII.

V. SOLITON RADIATION

The original version of a theory of AKR as soliton radiation was proposed by Galeev and Krasnoselkikh [1976], in which electron beams were assumed to be formed in the external region of the magnetosphere where $\omega_{pe} > \omega_{ce}$. Under these conditions, the electron beam could lose up to 50% of its energy to Langmuir wave excitation. When these waves are strong enough, the ponderomotive force can drive the modulational instability [Rudakov and Tsytovich, 1976], which creates density cavitons that trap the Langmuir waves. These are Langmuir solitons and they subsequently collapse and radiate at $\omega = 2\omega_{pe}$. (For a more detailed discussion of this process, see Maggs, [1978]).

The assumption $\omega_{pe} > \omega_{ce}$ disagrees with recent observations that show $\omega_{pe} < \omega_{ce}$ in the AKR source region. In the latter case, not only is the $\omega = 2\omega_{pe}$ radiation inaccessible to free space, but Langmuir solitons cannot exist or collapse at all. For those reasons Istomin et al. [1978] proposed a new version of the theory involving radiation from electrostatic electron cyclotron solitons, which can exist for $\omega_{pe} < \omega_{ce}$. The solitons collapse and radiate at $\omega \cong 2\omega_{ce}$. Istomin et al. estimate that the required efficiency necessary to produce observed levels of AKR is achievable if the ratio of beam to plasma density is $n_b/n_o \sim 3 \times 10^{-3}$. In a later paper, Cole and Pokhotelov [1980] showed that this theory is capable of explaining the power levels of AKR as well as other qualitative features of the radiation.

The principle problem with this theory is that the radiation frequency appears to be too high to lie in the observed narrow band just

above the right hand cutoff $\omega_R = 1/2 \left[\omega_{ce} + (\omega_{ce}^2 + \omega_{pe}^2)^{1/2}\right] < 1.05\ \omega_{ce}$ for $\omega_{pe}^2 << \omega_{ce}^2$, reported by Benson and Calvert [1979] and Benson et al. [1980]. However, it is conceivable that the source region has been misidentified so that the true source is higher than the region identified as the source from Isis I data. If the real source is about 1.25 times the identified geocentric attitude of the source region, the soliton radiation theory would be a possible AKR mechanism. This corresponds to a difference in height between the source and the Isis I AKR observations of 1500-2000 km. However, this possibility would be in contradiction to the recent conclusions by Calvert [1981] from the AKR gap signatures on Isis I ionograms that the AKR source could be no higher than 130 km above Isis I.

VI. LOSS CONE INSTABILITY

A mechanism involving unstable loss cone distributions was first proposed to explain the Io-modulated component of Jovian decametric radiation [Wu and Freund, 1977]. In that model, a fraction of the electrons in the Io flux tube which are accelerated by the Io-sheath became trapped in the Io flux tube because their pitch angle is larger than the local atmospheric loss cone. These electrons give rise to induced emission near their mirror points because of the loss cone free energy in their distribution function. Later, a loss cone model was proposed to explain the Io-independent decametric radiation [Goldstein and Eviatar, 1979].

The loss cone model was applied to AKR in Wu and Lee [1979] and Lee, Kan and Wu [1980]. In this version of the model, some of the electrons which are injected from the plasma sheet and magnetosphere are assumed to descend into the upper atmosphere (ionosphere) with varying pitch angles. Because of the converging magnetic field lines (magnetic mirror), there is a loss cone angle $\theta_{\ell c}$ given by

$$\left(\frac{B_{max}-B_{min}}{B_{max}}\right)^{1/2} = \cos \theta_{\ell c} \qquad (2)$$

where B_{max} and B_{min} are the maximum and minimum magnetic field encountered by the injected particles. Electrons with large pitch angles outside the loss cone, i.e., with velocity components

$$\frac{v_{\parallel}}{v_{\perp}} < \cos \theta_{\ell c} \qquad (3)$$

reflect and ascend back into the aurora. These ascending electrons thus have a loss cone distribution (see Figure 6).

Wu and Lee use the following dispersion relations for the two modes

$$1 - \frac{c^2k^2}{\omega^2} + \frac{\omega_{pe}^2}{\omega^2 n_o}\int d^3\vec{v}\left[\omega_{ce}\frac{\partial f_e}{\partial v_\perp} + k_\parallel v_\perp \frac{\partial f_e}{\partial v_\parallel}\right]\frac{v_\perp J_1'^2(b)}{(\omega-\omega_{ce}/\gamma-k_\parallel v_\parallel)} = 0 \text{ (X-mode)}$$

$$1 - \frac{c^2k^2}{\omega^2} + \frac{\omega_{pe}^2}{\omega^2 n_o}\int d^3v\left[\omega_{ce}\frac{\partial f_e}{\partial v_\perp} + k_\parallel v_\perp \frac{\partial f_e}{\partial v_\parallel}\right]\frac{v_\parallel^2 J_1^2(b)}{v_\perp(\omega-\omega_{ce}/\gamma-k_\parallel v_\parallel)} = 0 \text{ (O-mode)} \quad (4)$$

where $J_1(b)$ is the Bessel function of first order, $b = k_\perp v_\perp/\omega_{ce}$, and $\gamma \sim 1 + 1/2\,\frac{v_\perp^2}{c^2}$ is the relativistic term which couples the perpendicular electron motion to the waves. Thus relativistic effects allow the free energy of the loss cone distribution to be absorbed by the electromagnetic waves in the model.

A typical set of growth rates found by Wu and Lee from the dispersion relation is shown in Figure 7. It is seen that the X-mode grows faster than the O-mode in this model. This is to be expected, since the X mode interacts with the particles to a much greater extent, and thus could absorb the free energy of the loss cone easier. Thus the X-mode is expected to be the dominant polarization, in agreement with observation. If one includes higher harmonic terms in the

dispersion relation, which have $\omega - m\omega_{ce}/\gamma + k_{\parallel}v_{\parallel}$ in the denominator, the theory might well yield a harmonic band structure with resonances near $\omega \sim m\omega_{ce}/\gamma + k_{\parallel}v_{\parallel}$ for $m = 1, 2, 3, \ldots$. Wu and Lee introduced a local density-depleted cavity in the aurora which they assumed to be present to provide a waveguide for wave growth by multiple reflection off of its boundaries, and ultimate free space accessibility. From the Benson and Calvert determination $\omega_{pe} \sim 0.2\ \omega_{ce}$, $\omega > \omega_R \sim 1.04\ \omega_{ce}$ is the minimum required frequency for propagation. This puts the growth rate in Figure 6 an order of magnitude below its maximum shown.

Although the normal loss cones in the lower aurora have $\theta_{\ell c} \lesssim 18°$, Mizera and Fennell [1977] have reported enhanced loss cones of $30° \lesssim \theta_{\ell c} \lesssim 60°$ apparently produced by large parallel electric fields. This is to be compared with $\theta_{\ell c} \cong 56.5°$ in Fig. 7. Thus, enhanced loss cones appear adequate to produce AKR, even though the ordinary loss cones are not (since they are too small to cause instability). Future satellite missions could help establish or disestablish this mechanism by studying the correlation in space and time of AKR with the loss cones.

In the later paper, Lee, Kan and Wu [1980] expand their theory to include dispersive effects in their growth rate. They predict that AKR produced by their mechanism would lie between 2000 km and 9000 km in altitude. They also note the theory predicts a close correlation between AKR and the inverted V events.

A shortcoming of the theory is the fact that it predicts the wave direction to be upgoing (in the direction of the loss cone particles), propagating almost perpendicular to the magnetic field. Observation shows the wave is downgoing, making an angle θ with respect to the magnetic

field, where $60° < \theta < 90°$ [James, 1980]. This discrepancy must be cleared up before the theory can be accepted as the mechanism for AKR.

VII. NONLINEAR BEATING OF ELECTROSTATIC WAVES

The use of electrostatic waves to produce electromagnetic AKR was originally proposed by Barbosa [1976]. Barbosa considered the incoherent beating of upper hybrid waves ($\omega \sim \omega_{uh}$, where ω_{uh} is the upper hybrid frequency) and used the random phase approximation to treat the interaction. He found that the electric fields of the upper hybrid wave had to be > 3 V/m to generate the power levels observed for AKR.

Because required amplitudes for upper hybrid waves to produce AKR by the incoherent mechanism appear unreasonably high, Roux and Pellat [1979] proposed a coherent mechanism. In the latter theory, the source of energy is again electrostatic waves, which are driven unstable by the auroral electron beams. These waves can exist in two high frequency regimes for which solutions to the electrostatic dispersion relation are possible:

(1) $\omega_{\ell h} < \omega < \min(\omega_{pe}, \omega_{ce}) = \omega_{pe}$

(2) $\max(\omega_{pe}, \omega_{ce}) = \omega_{ce} < \omega < \omega_{uh}$

In the inhomogenous plasma medium, electrostatic waves propagating toward decreasing density and/or magnetic field approach the upper and lower hybrid resonances: $\omega = \omega_{uh}$ and $\omega = \omega_{\ell h}$. The waves undergo a geometrical amplification near these resonances and a large amplitude narrow spectrum of waves develops there. Thus, a large amount of electrostatic energy develops near the hybrid resonances.

The electrostatic hybrid resonance energy may be converted into electromagnetic waves by a nonlinear three wave process: $\ell + \ell \rightarrow t$. Four possible variations may occur:

(1) $\omega_{\ell h} + \omega_{uh} \rightarrow$ O mode at $\omega \approx \omega_{uh}$

(2) $\omega_{\ell h} + \omega_{uh} \rightarrow$ X mode at $\omega \approx \omega_{uh}$

(3) $\omega_{uh} + \omega_{uh} \rightarrow$ O mode at $\omega \approx 2\omega_{uh}$

(4) $\omega_{uh} + \omega_{uh} \rightarrow$ X mode at $\omega \approx 2\omega_{uh}$

Case (2) was ruled out because of the inaccessibility to free space arising from the evanescent layer between ω_{uh} and ω_R. Roux and Pellat's evaluation of the other three processes shows case (4) is the most probable and efficient, producing greater amplitudes than the other two. Thus the predicted polarization is correct, but the predicted frequency is apparently twice that observed. However, this frequency may still be viable if the source is substantially higher than the region identified as the source from current satellite data (see discussion in Section V on this issue).

For reasonable electron beam velocities and expected generated energies of upper hybrid waves, Roux and Pellat find AKR field amplitudes of a maximum of $E \sim 40$ mV/m may be created in the source. Isis I measurements indicate E fields of ~ 4 mV/m at $f \sim 500$ kHz, and would be expected to be 3 to 10 times this at the peak frequency. Thus the homogenous theory of Roux and Pellat gives a (marginally) adequate amplifying efficiency. Large density inhomogeneities and fluctuations may reduce this efficiency.

Although case (4) was picked to be the prevailing process, James [1980] has pointed out that a modified version of case (2) may be a viable process. Since $\omega_{\ell h} + \omega_{uh}$ is quite close to the X-mode cutoff frequency, replacing the lower hybrid wave with a wave of slightly higher frequency

would put it above cutoff. In particular, James proposes combining a whistler wave with $\omega > \omega_{\ell h}$ with a z-wave (slow, quasistatic X-mode in range $\omega_{ce} < \omega < \omega_{uh}$). Jones [1977] presented an earlier version of that theory. This area needs further investigation.

Two other areas must be investigated with respect to this theory, in addition to resolving the frequency question. One is the question as to whether the theory can predict the angular spectrum $60 < \theta < 90°$. The other is whether there are large amplitude upper hybrid waves (z-waves) in the AKR source region (whistlers are known to be there), and whether a correlation between the two can be established.

VIII. BEAM AMPLIFICATION OF ELECTROMAGNETIC WAVE VIA COHERENT EIC DENSITY FLUCTUATIONS

In the proposal of Grabbe et al. [1980], electromagnetic noise interacts with low frequency coherent quasineutral density fluctuations created by EIC waves, in the presence of precipitating auroral electron beams. The result is a three wave (parametric) process, in which beat waves are produced which can interact with the beam, much like the theory of Palmadesso et al. [1976]. It was found that when wave frequency was just below the Doppler shifted beam cyclotron frequency, $\omega < \omega_{ce} + k_z v_b$, and the polarization in the X-mode the electromagnetic wave would undergo a convective instability. The basic requirements for this instability were found to be:

(1) Minimum beam density:

$$\left(\frac{n_b}{n_o}\right) > \frac{k_z(\Delta v)^2}{2\omega_{ce} v_b} \tag{5}$$

where Δv is the thermal beam velocity spread.

(2) Accessibility to free space: $(\omega > \omega_R)$

$$\omega_{pe}^2 < k_z v_b \omega_{ce} \tag{6}$$

Combining the limitations on frequency for instability and accessibility to free space gives a predicted radiation band in the narrow range

$$\omega_{ce} + \frac{\omega_{pe}^2}{\omega_{ce}} < \omega < \omega_{ce} + k_z v_b \tag{7}$$

just above the right hand cutoff, provided the upper limit is greater than the lower limit (i.e., that Eq. (6) is satisfied.) Furthermore, combining Eqs. (5) and (6), we have a limitation on the parallel component of the wave vector:

$$\frac{\omega_{pe}^2}{v_b \omega_{ce}} < k_z < \frac{2\omega_{ce} v_b n_b}{(\Delta v)^2 n_o} \qquad (8)$$

This equation typically limits the wave propagation direction to be almost (but not quite) perpendicular to the magnetic field. Both predicted limitations on frequency and wavenumber are in excellent agreement with the Isis I measurements [Benson and Calvert, 1979].

Several other predictions can be made from the restrictions given by Eq. (5)-(8). Eq. (6) typically yields $\omega_{pe} < 0.2\ \omega_{ce}$, in excellent agreement with the Isis I measurements. This requires local depletion of the density at the source and may give rise to a density waveguide which allows for long growth lengths by multiple reflection off of its boundaries, much as in the Wu-Lee theory. Typical spatial growth rates are shown in Figure 8. Typical total growth lengths of L ~ 100 km were found to be adequate to produce observed AKR power levels from electromagnetic noise. The O-mode has no frequency which gives an instability, hence the predicted polarization is that of the X mode, as observed. Furthermore, because of the restrictions in Eqs. (5) and (7), local temporal variations in plasma density, magnetic field, beam velocity and beam spread in regions of marginal stability may shut the radiation on and off. This could explain the bursty nature of AKR. Finally, a warm plasma theory yields further unstable frequency ranges at $\omega \gtrsim n\omega_{ce} + k_z v_b$ for n an

integer. Some evidence for such a harmonic band structure was obtained by the Isis I data.

All of the above conclusions were based on a steady state model analysis, in which the energy in the density fluctuations was assumed to be replenished by the beam or other sources at approximately the same rate as it was being used up. However, the Feynman diagram for the three wave interaction (Figure 9) reveals that a more dynamical process is taking place. Not only is energy being resonantly transferred from the density fluctuations to the electromagnetic wave in the appropriate frequency band because of the beam, but the energy the beam injects into the beat wave is being transferred back to the density fluctuations and the electromagnetic wave because of a finite three-wave coupling coefficient. This coupling coefficient was ignored in the steady state theory, but must be included to understand the full dynamical process.

A set of coupled nonlinear rate equations for the evolution of each of the three waves in Figure 9 were analyzed by Grabbe [1981]. The results show that observed power levels of AKR can be obtained for growth rates found in the steady state theory. It was found that convection out of the resonant region appears to be more important in causing the growth to saturate than nonlinear saturation.

In summary, this model of AKR provides several predictions which are in good agreement with observation. However, an important assumption of the model is that low frequency density fluctuations (assumed to be produced by coherent EIC waves like those seen by Lysak et al. [1980] and Temerin et al. [1979]) play an important part in AKR. EIC waves have been observed in the range of 5000 km to 8000 km altitude (2-3 R_E) in the

aurora, which is also the general source region of the most intense AKR. However, observations of EIC waves below 5000 km are rare, even though AKR is observed down to about 3000 km (1.5 R_E). Other types of low frequency density fluctuations could easily be used in this mechanism; EIC waves are not necessary, they are just the most likely candidate. There have not been, however, sufficient measurements at the low altitudes for valid statistics. Future observational studies are necessary to see if the low altitude coherent density fluctuations are present and to investigate the correlation of density fluctuations or EIC waves with AKR.

IX. SUMMARY

A variety of plasma theories have been proposed for AKR. It was seen that only three give the correct prediction of both the frequency and polarization of the AKR: Melrose [1973], Wu and Lee [1979] and Grabbe et al. [1980]. (The possible modification of the Roux and Pellat theory would also be capable of predicting these.) All three of these are favored by the local depletion of the density in the source region and give very precise predictions as to what this density should be for a given local magnetic field. However, one of these (Melrose) predicts auroral electron distribution functions with large anisotropies, which is not supported by available measurements of the auroral electron distribution functions. This leaves the theories of Grabbe et al. and Wu and Lee. Both theories are capable of predicting several other observed properties of AKR, although the Wu and Lee theory has a problem with the direction of propagation of the radiation. A crucial test of the theory of Grabbe et al. will be establishing a correlation between AKR and low frequency density fluctuations, as well as finding the low frequency density fluctuations in the lower altitude AKR source. A crucial test of the Wu and Lee theory will be establishing a correlation between AKR and the enhanced loss cones.

Four comments are in order on the comparisons made with available observations. First is the possibility that future satellite missions might find the large anisotropy of the auroral electron distribution functions required by the Melrose theory. Second is the possibility that available measurements of the AKR source region are sufficiently inaccurate that the theories of Istomin et al. and Roux and Pellat, which

predict a frequency at close to twice the observed local right hand cutoff, might be viable. However, both of the possibilities seem rather improbable in light of the abundance of the data on these matters. Third is the possibility that modifications of one or more of these theories, such as the proposed modification of the Roux and Pellat theory, may yield a more promising theory in the same way that a modification of the theories of Melrose, Palmadesso et al. and Galeev et al. yielded the more promising theories presented in Wu and Lee, Grabbe et al. and Istomin et al., respectively. A final point is that the mechanisms proposed by Istomin et al. and Roux and Pellat, which cause radiation at twice the observed frequency, may contribute to the first harmonic of any harmonic band structure of AKR.

ACKNOWLEDGEMENTS

I would like to thank Peter Palmadesso and Robert Benson for a critical reading of the manuscript, and C. S. Wu and R. L. Kaufmann for allowing me to reproduce figures from their paper.

This work was supported by the Office of Naval Research and the National Aeronautics and Space Administration Grant NGL-16-001-043 with NASA Headquarters.

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FIGURE CAPTIONS

Fig. 1 Three dimensional plots of the electron velocity distribution functions observed in the lower aurora. (From Kaufmann and Ludlow, 1980.)

Fig. 2 Schematic of the double mode conversion process in the inhomogenous plasma, proposed in the theory of Oya and Benson.

Fig. 3 Dispersion relation of the extraordinary (X) mode, showing the fast (FX) and slow (SX) wave branches. The band of observed AKR frequencies is indicated. ω_L and ω_R are the left and right hand cutoffs, respectively.

Fig. 4 Dispersion relation of the ordinary (O) mode.

Fig. 5 Diagram showing the frequency ranges in which electrostatic waves can exist, which occur when $K_\perp/K_\parallel$ is negative.

Fig. 6 A loss cone velocity distribution function, in which the low velocity particles ($v_\parallel/v_\perp < \cos \theta_{lc}$, where θ_{lc} is the loss cone angle) are missing.

Fig. 7 Plots of the growth rates for the X-mode and O-mode just above the cyclotron frequency in the theory of Wu and Lee for a loss cone angle of $\theta_{lc} \sim 56.5°$. (From Wu and Lee, 1979.)

Fig. 8 Growth lengths of the X mode found in the theory of Grabbe et al. for beam velocity $v_b = 0.2\ c$, thermal spread $\Delta v = 0.3\ v_b$ and beam $n_b \cong 10^{-2}\ n_o$, with n_o the plasma density. A frequency of $f \sim 200$ kHz was assumed. Here the horizontal axis is the ratio of the wavenumber of the electromagnetic wave to the ion wave, and $\epsilon = \delta n/n_o$ is the ratio of the density fluctuation to the background density. (From Grabbe et al., 1980.)

Fig. 9 A three-wave Feynman diagram used to study the dynamical evolution of AKR. Processes indicated by the numbers are: (1) Induced absorption (2) Beam amplification (3) Induced emission. Here W and γ are the coupling coefficient and growth rates that appear in the rate equations.

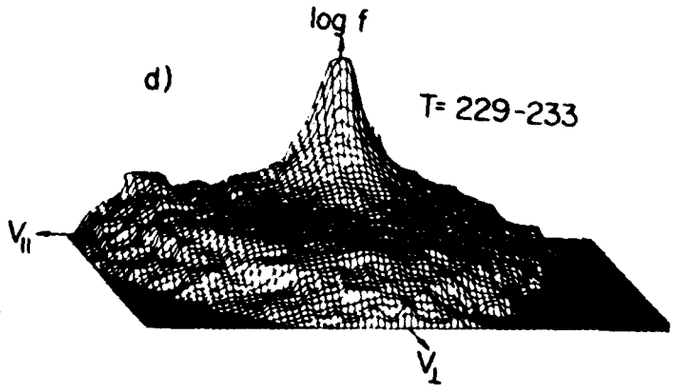


Figure 1

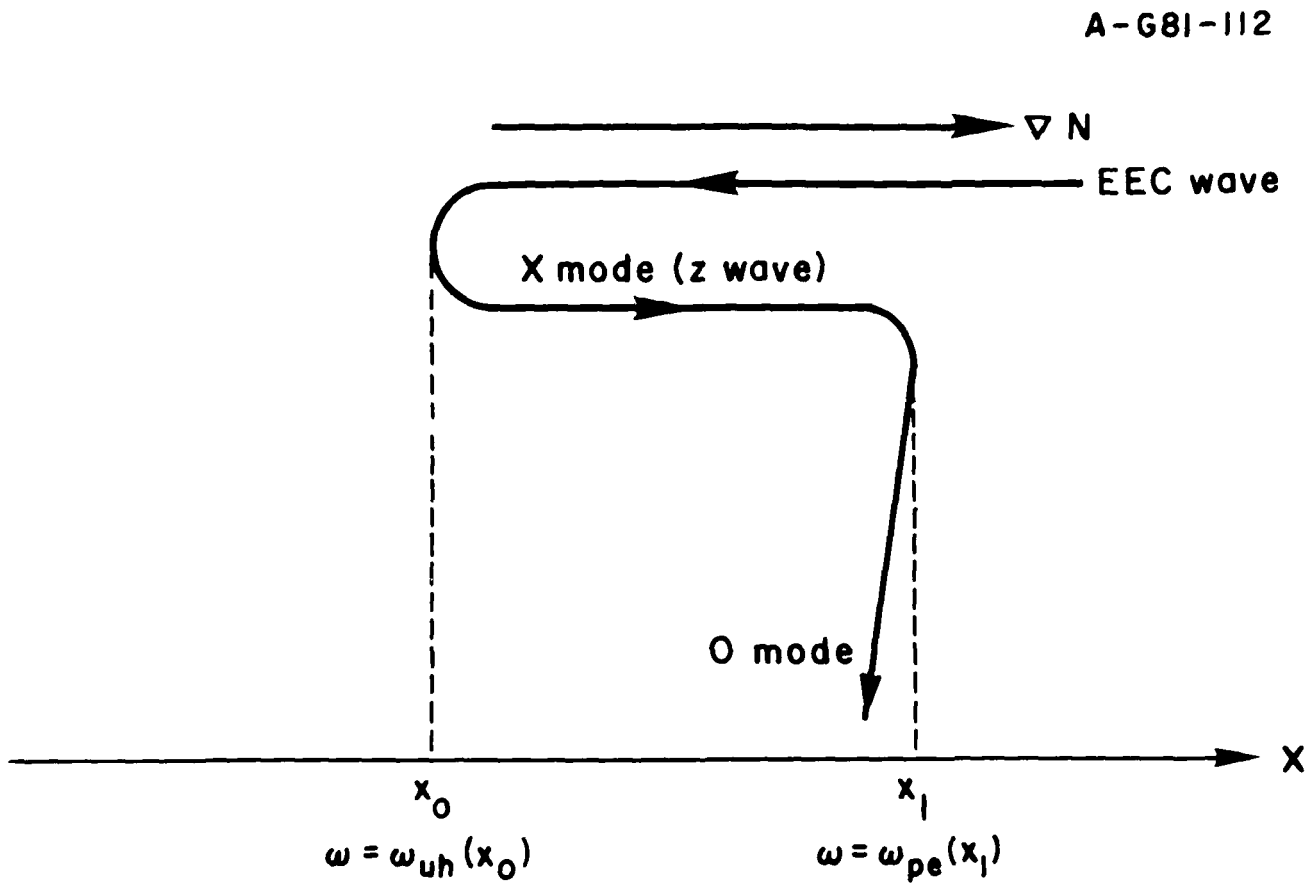

A-G81-112
∇ N
EEC wave
X mode (z wave)
O mode
X
x_0
$\omega = \omega_{uh}(x_0)$
x_1
$\omega = \omega_{pe}(x_1)$

Figure 2

A-G81-113

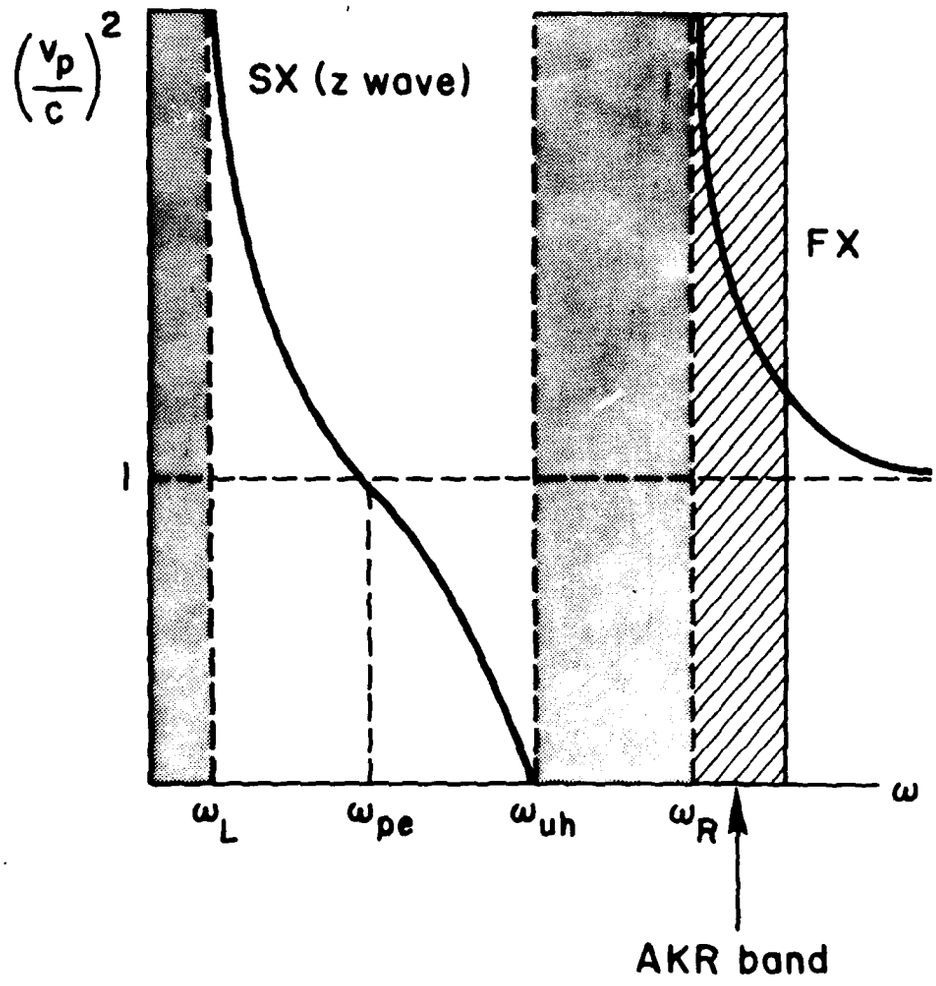


Figure 3

A-G81-115

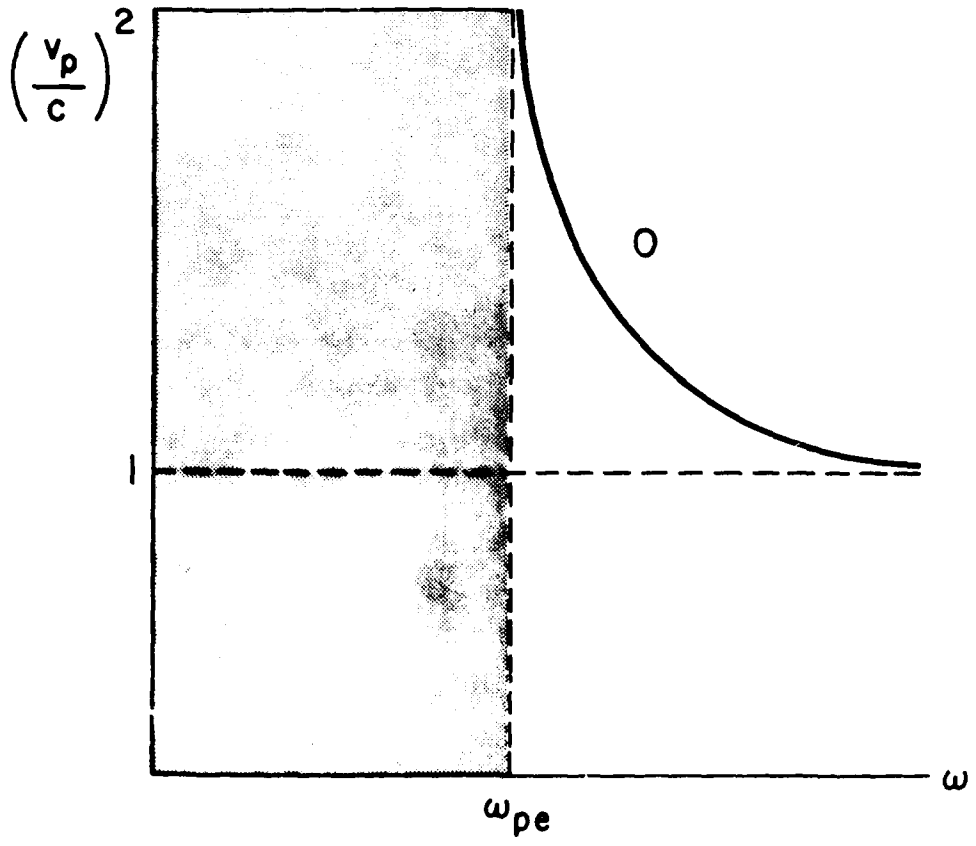


Figure 4

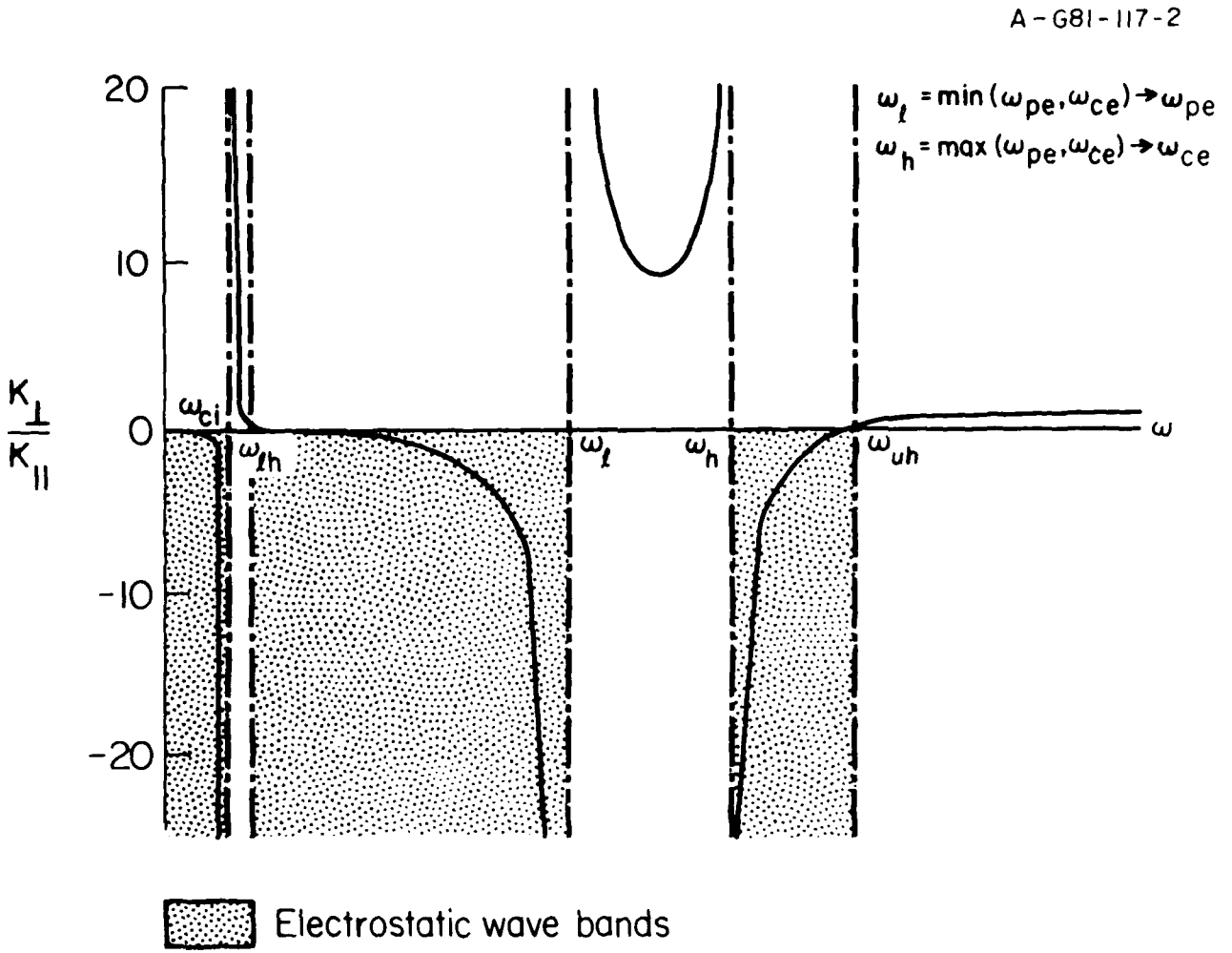

A-G81-117-2
20
10
0
-10
-20
$\frac{K_\perp}{K_{||}}$
ω_{ci}
ω_{lh}
ω_l
ω_h
ω_{uh}
ω
$\omega_l = \min(\omega_{pe}, \omega_{ce}) \rightarrow \omega_{pe}$
$\omega_h = \max(\omega_{pe}, \omega_{ce}) \rightarrow \omega_{ce}$
Electrostatic wave bands

Figure 5

A-681-116-1

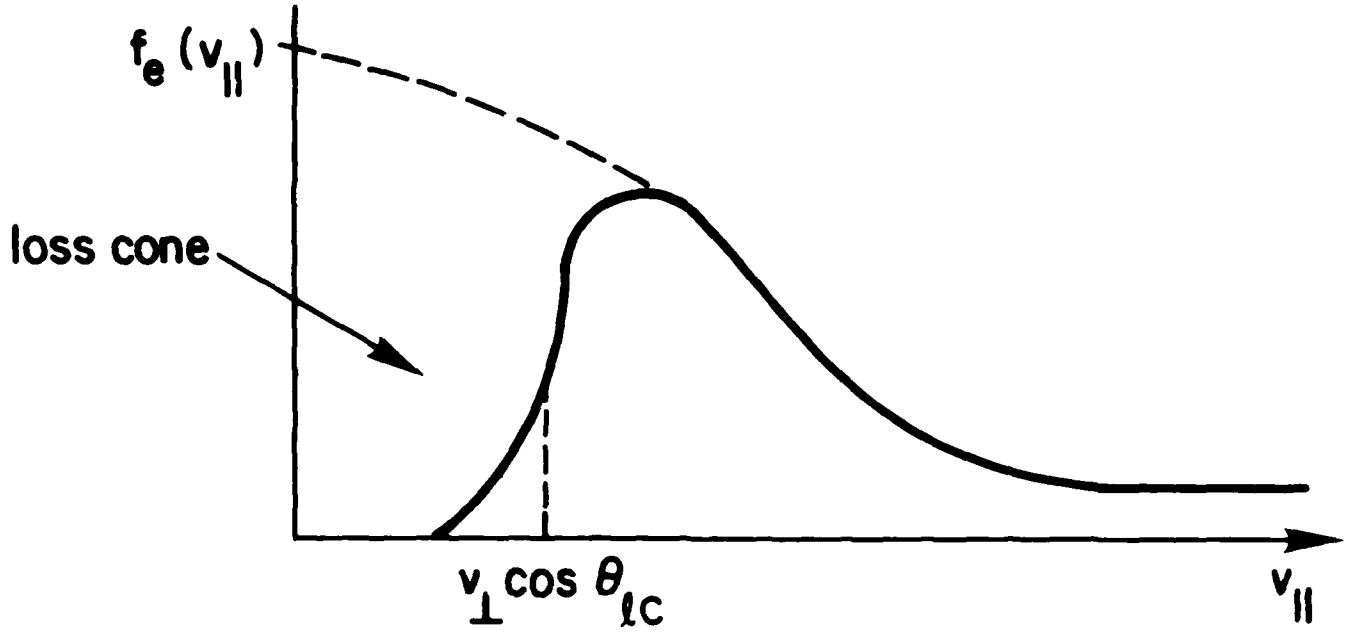


Figure 6

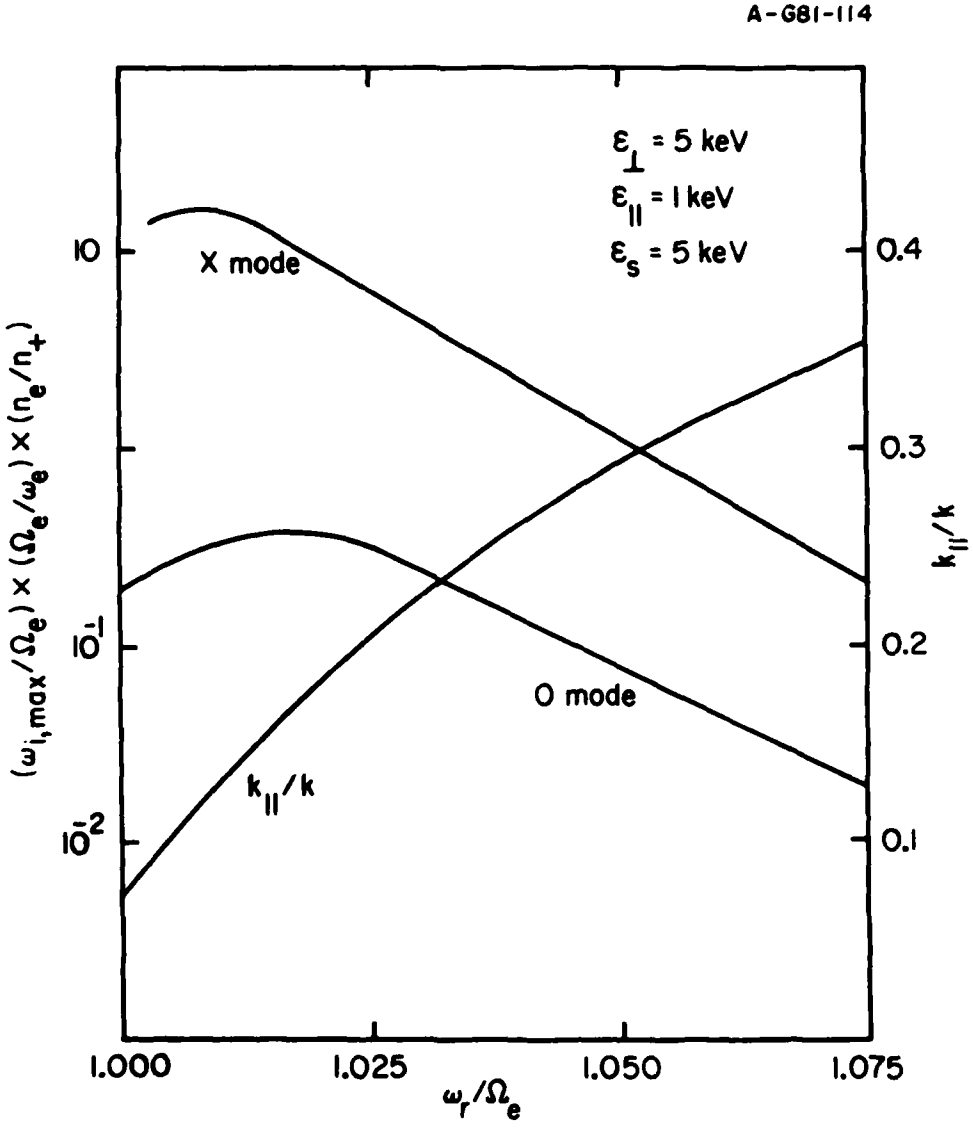

A-G81-114
$\varepsilon_\perp$ = 5 keV
$\varepsilon_{||}$ = 1 keV
ε_s = 5 keV
X mode
O mode
$k_{||}/k$
10
10^{-1}
10^{-2}
0.4
0.3
0.2
0.1
$k_{||}/k$
1.000
1.025
1.050
1.075
ω_r/Ω_e
$(\omega_{i,max}/\Omega_e) \times (\Omega_e/\omega_e) \times (n_e/n_+)$

Figure 7

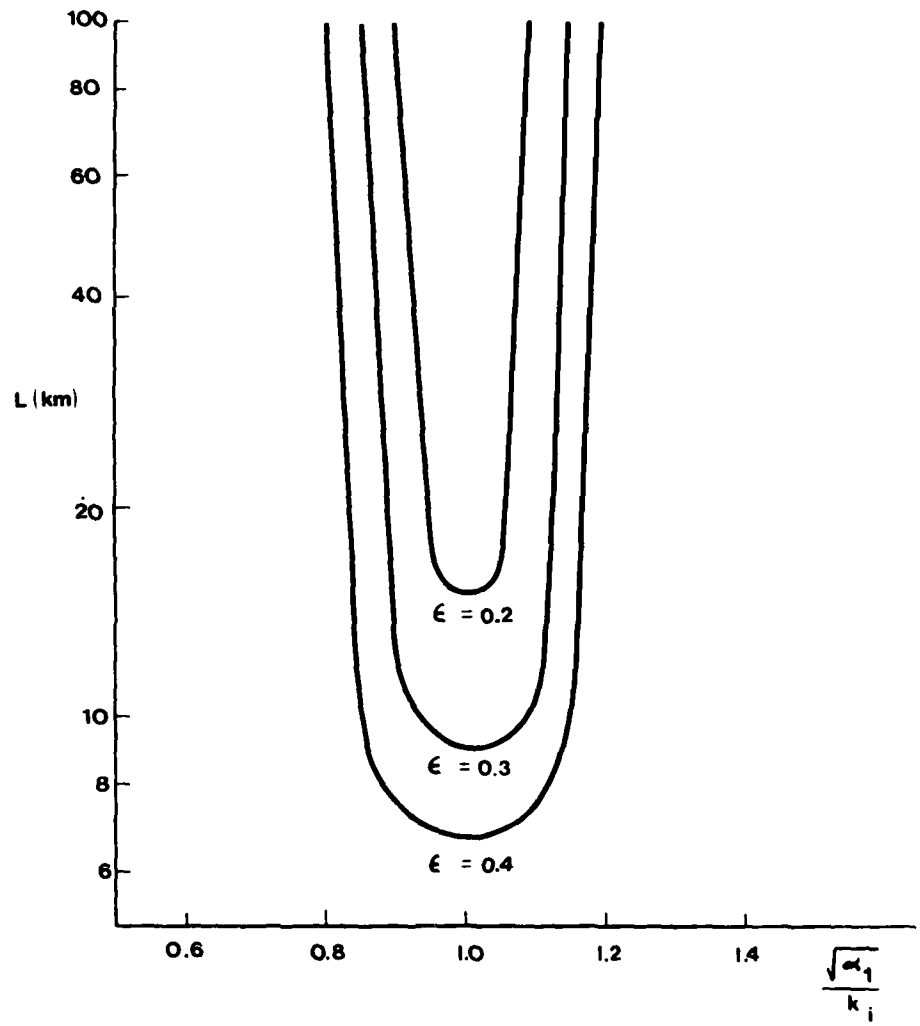

100
80
60
40
L (km)
20
10
8
6
ϵ = 0.2
ϵ = 0.3
ϵ = 0.4
0.6
0.8
1.0
1.2
1.4
$\frac{\sqrt{\alpha_1}}{k_i}$

Figure 8

A-G81-215

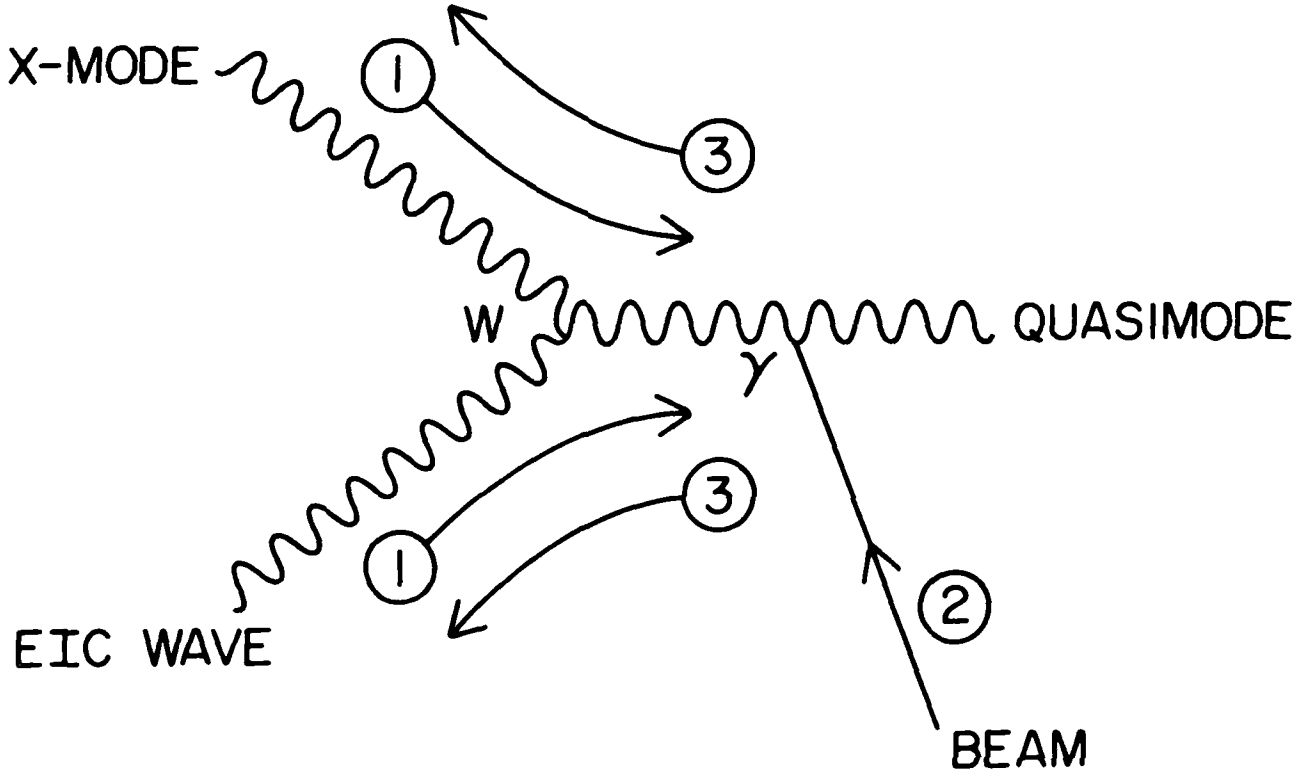
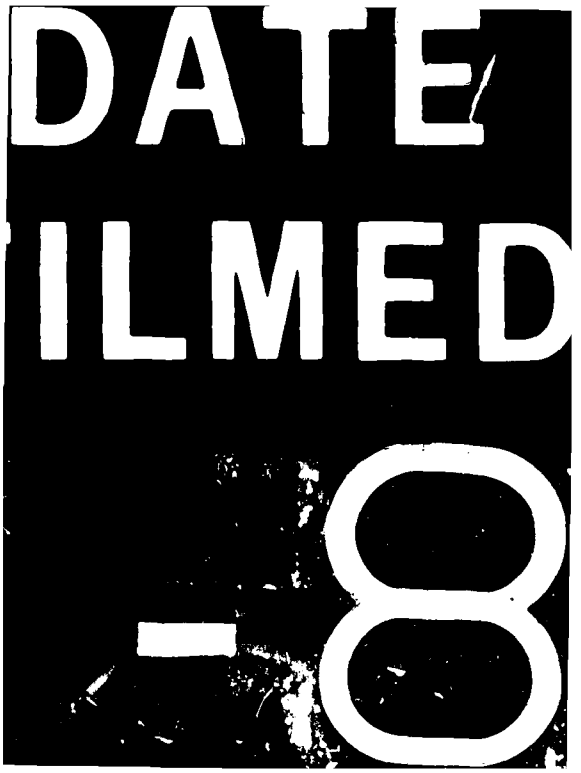


Figure 9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